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Analysis of in situ water velocity distributions in the lowland river floodplain covered by grassland and reed marsh habitats - a case study of the bypass channel of Warta River (Western Poland)

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Abstract: The analysis of in situ measurements of velocity distribution in the floodplain of the lowland river has been carried out. The survey area was located on a bypass channel of the Warta River (West of Poland) which is filled with water only in case of flood waves. The floodplain is covered by grassland and reed marsh habitats. The velocity measurements were performed with an acoustic Doppler current profiler (ADCP) in a cross-section with a bed reinforced with concrete slabs. The measured velocities have reflected the differentiated impact of various vegetation types on the loss of water flow energy. The statistical analyses have proven a relationship between the local velocities and the type of plant communities.

Keywords: Floodplain vegetation; Flow resistance; In situ measurements; Velocity distribution.

INTRODUCTION

The floodplain vegetation is the most important factor determining the flow conditions during flood events (Naden et al., 2006; Petryk and Bosmajian, 1975). Its influence on the flow transformation must be considered in water resource management and flood protection. The vegetation of floodplains increases the flow resistances and affects the floodplain capacity and the water level and in this way is deteriorating the flow conditions and increasing the flood risk. On the other hand, plant cover is beneficial for the biodiversity of floodplains and numerous environmental protection programmes have been introduced on floodplains limiting sward mowing or grazing. The control of the vegetation expansion is also limited due to the economic factor. In many countries (including Poland), financial expenditure on development and maintenance of flood control infrastructure have been cut down. The current management of water resources and flood control systems must therefore take into account the impact of various plants on the flow conditions.

A very useful approach for describing and classifying vegetation is phytosociology (Biondi, 2011; Dierschke, 1994). It assumes that the variety of form and structure of plants repeats themselves in similar environmental conditions (soil type, slope and moisture regime). The vegetation units have been identified, described and classified according to phytosociological criteria. The worldwide vegetation classification enables to collect and report vegetation information in a standard format and present a spatial distribution of standard vegetation units on maps. This classification is a critical support tool for monitoring, research and management of biological resources. Recently, some implementation issues are addressed within the context of the objectives of the EU Habitats Directive (92/43/EEC), concerning the recognition of habitats and the definition of management plans (Biondi, 2011). In terms of river bed hydraulics it is proved that different types of vegetation represent species canopy with which the specific structure determining the flow resistance is associated (Petryk and Bosmajian, 1975).

Many scientific institutions carry on researches on the impact of vegetation on flow conditions in an open channel network since the beginning of the 1970s (e.g. Klaassen and Van der Zwaard, 1974). These include theoretical principles of the mathematical modelling of the phenomenon (Baptist et al., 2007; Horritt, 2006; Klopstra et al., 1997; Wu et al., 2001; Yang and Choi, 2010), numerical modelling with models of varying complexity (Crosato and Saleh, 2011; Perona et al., 2009; Velasco et al., 2008), flume experiments to verify models of vegetation roughness and in situ floodplain roughness estimations (Meijer and van Velzen, 1999; Murphy et al., 2007; Straatsma, 2009; Tal and Paola, 2010). Some studies focused on the accumulation of both thick and fine debris (Mazur et al., 2016) carried along with the flood wave.

The amount of surveys focused on relationship between floodplain vegetation and flow conditions is still not efficient. Vargas-Luna et al. (2015) analysed the performance of a large number of models on flow resistance, vegetation drag bed-shear stresses in vegetated channels to provide information for modelling purposes. The summary of measurements using real vegetation presented in this paper indicated a very small number of works referring directly to field measurements (Nikora et al., 2008; Ree and Crow, 1977). Also Straatsma (2009) noticed the very small number of studies on „in situ floodplain roughness estimation during overbank flooding". This is mainly caused by the difficulties in finding sites ensuring both the measurement requirements and security of the research teams.

The development of mobile measurement technologies allows to conduct a wide range of reliable measurements of the velocity (e.g. ADCP measurement device) and water level coordinates (high-precision geodetic GPS equipment or laser tachometers). Mobile measurement kits enable the performance of measurements in an optimal period (from the analytical point of view), however they still require a prepared survey site.

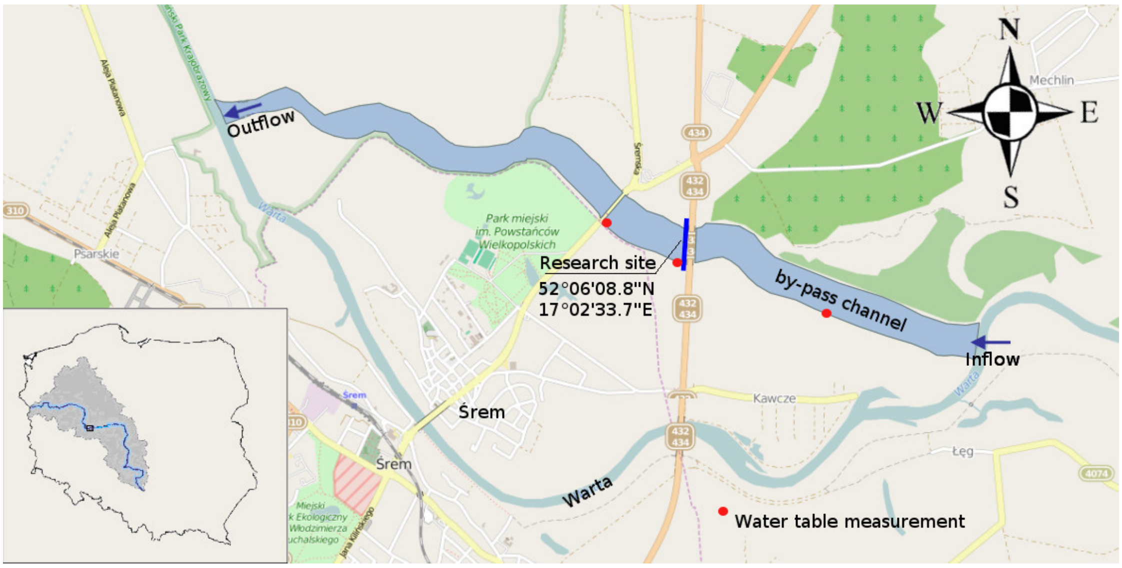

Fig.1. Localization of research site.

The main objective of this study has been the analysis of the impact of the specific herbaceous plant species on the distribution of vertical averaged velocities in a flood area based on measurements taken during flood event via the bypass channel. Velocity measurements have been compared with the types of vegetation both above and below the measured profile. We hypothesised that the various types of vegetation influence the diversification of velocities during flood events.

MATERIALS AND METHODS

Description of the research site

The survey site was located on the Warta river bypass channel, near to the Śrem town (Fig. 1). The bypass channel was constructed in the beginning of 1970s as an element of flood protection system of the town. According to the design assumptions it was supposed carry approx. 50% of flow with a probability of occurrence of 1%. The channel is filled when the flow rate of Warta exceeds 220 m^3/s (as measured in June 2013). In other periods, the area is used as a meadow. Due to the decreasing profitability of farming and flood protection budget drop, the regular mowing pasture management was highly limited. A strong expansion and growth of various plants took place, affecting flow conditions during flood events (Figs. 2 and 3).

The measurements were carried out nearby a road bridge. During its construction, a temporary concrete road (2.5-metres wide) was built below the bridge (Fig. 3). The road was not demobilised after the bridge was constructed and it now constitutes the only part of the channel which is not covered with vegetation. The lack of plants on this narrow transect enabled hydrometric measurements with the ADCP StreamPro device (Teledyne Instruments, 2008). This kind of equipment requires a stable bed without vegetation to carry out reliable measurements. It is worth noting that the cross-section is situated in the densely vegetated area where velocity distribution depends mainly on the type of upstream and downstream growing plants, and the bed roughness is marginal. The bridge pillars also disturb the flow, they cause a local increase of water velocity, which could not be dissipated by approx. 6 m vegetation strip downstream the pillars. In order to minimize the impact of the bridge pillars on the analysis of the results, measurements made below the pillars ware excluded from the analyzed set.

Fig. 2. Research site – view from the north.

Fig. 3. Research site – view from the south.

The flat bed was an important advantage of the survey location. The water flow was determined mainly by a down river water surface slope and vegetation growing on the flow area.

Field measurements

Hydrometrical measurements of a flood wave in 2013

The measurements were performed during the flood event in June. It is a period of extensive vegetation development and probably perfect time to compare influence of various plants on water flow. Some seasonal changes to flow resistance conditions of the vegetation can be expected due to the plant development as well as agricultural practices. It is obvious that the flow resistance due to vegetation will also change with the duration of flooding. Nevertheless, the measurements completed in June, with the uncut sword, can be treated as a reference of the potential differentiation of the flow resistance of various types of vegetation.

During the flood in springtime 2013 the surveyed channel took over a small share of the Warta's total flow. The channel was filled on 9th of June and reached its maximum flow rate on 17th June 2013. The maximum rate of the bypass channel was 14.2 m^3/s and in Warta –245 m^3/s. Four flow measurements were completed with ADCP StreamPro in the hydrometric cross-section (Fig. 1). The summary is provided in Table 1. In the further, detailed analysis of velocities, the measurements taken on 17th June 2013 were used. Also measurements of water table elevations in point 1, 2 and 3 were performed (Fig. 1) with the geodetic GPS Sokkia GRX 1 measurement device operating in RTK mode. The water surface slopes on 17th June 2013 between points 1 and 2 amounted to 0.019% and 0.041% between points 2 and 3.

The scope of measurement data available from the ADCP SteamPro probe is very extensive (Teledyne RD Instruments, 2008). Among others, it is possible to gain information on vertical and horizontal velocities, water flow directions, water depth etc. A wide range of possible measurements has been described in various studies (Malcolm et al., 2008) and the user guide (Teledyne RD Instruments, 2008). The measurement data gained by the ADCP probe are available with the Winriver II application. This application allows also for the export of selected measurement data in the form of formatted text files which may be imported to other analytical software. The Winriver II presentation screen for the June 17th 2013 survey was presented on Fig. 4. The collected data included a small number of bad measurements (less than 5% of all measurements).

Table 1. Basic measurements data obtained during the flood in 2013 (the Warta River in Śrem).

Date	Location	Flow rate	
		Q [m^3/s]	
10.06.2013	Warta River	219.0	223.5
	Bypass channel	4.5	
14.06.2013	Warta River	235.5	245.2
	Bypass channel	9.7	
17.06.2013	Warta River	245.0	259
	Bypass channel	14.0	
23.06.2013	Warta River	232.0	238.1
	Bypass channel	6.1	

Diversification of vegetation of the survey site

The vegetation survey was carried out in a 20 metres wide buffer upstream and 20 metres downstream of the hydraulic measurement profile (concrete road next to the bridge). The relevé method of sampling plant communities was applied (Dierschke, 1994). As many as 16 relevés were surveyed upstream and 22 downstream. All the plant species were identified and their abundance was estimated. Basing on the plant species composition, the syntaxonomical classification of the vegetation was completed according to Dierschke (1994).

RESULTS

Analysis of vertical velocity profiles

The set of ADCP StreamPro measurement data included three components of the velocity vector on the specific measurement levels. Eight measurement levels were identified. Approximately 200 vertical velocity profiles were measured. A large variability caused by the diversity of vegetation was revealed. According to the qualitative analysis, the three types of forms were the most frequent, as presented on Fig. 5.

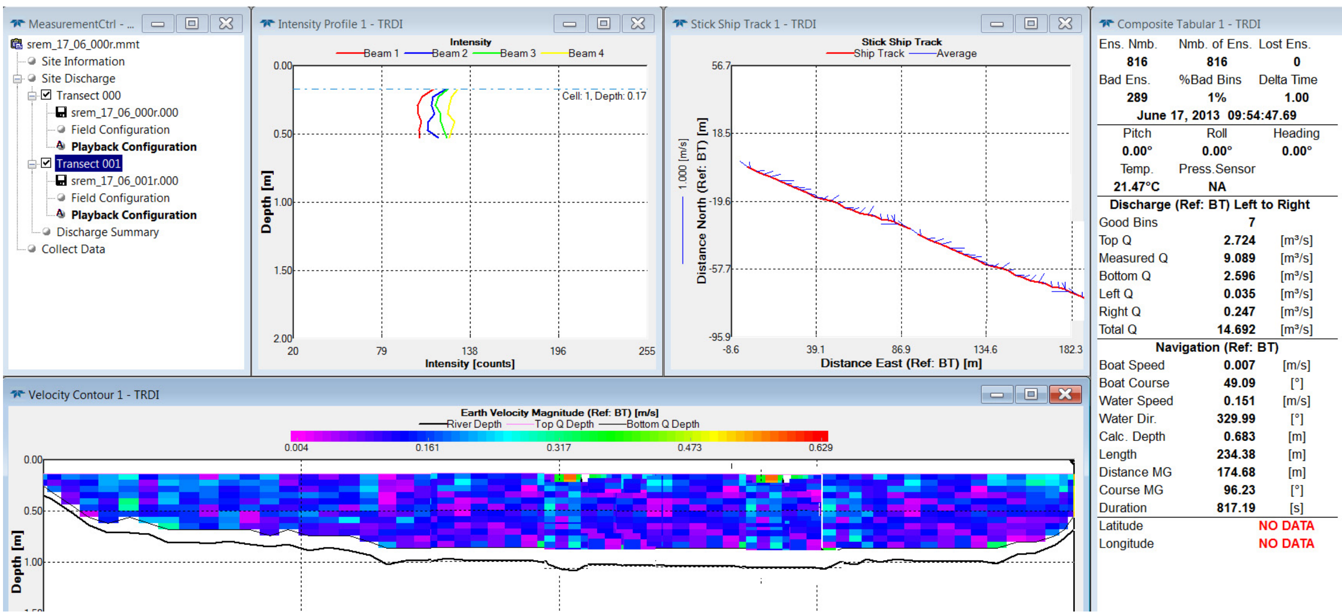

Fig. 4. Screen of the WinRiver II application with the measurements taken on 17th June 2013.

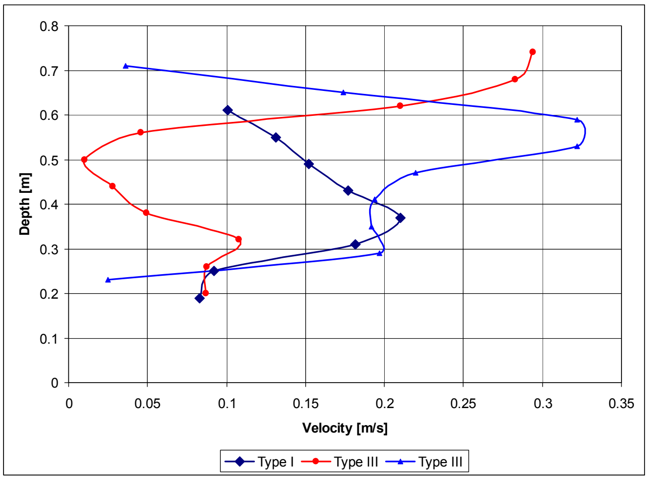

Fig. 5. Example of vertical velocity profiles.

Preliminary analysis showed the lack of statistical relationships between type of velocity profiles and the plant species. It has directed our further research towards the use of vertical averaged values of velocity which could reflect the energy losses caused by vegetation.

Horizontal distribution of velocity in a hydrometric cross-section

The vertical averaged values of velocity along the hydrometric cross-section are presented in Fig. 6. Similarly to vertical profiles, the horizontal distribution was highly variable. This confirms that the flow conditions are determined not only by the morphology of the area, but also by vegetation. It must be underlined that the bed level of the measurement cross-section and adjacent areas were not significantly changed (mean difference was 0.1 m), therefore the impact of local elevation slops was very limited. The changes of flow direction were caused mainly by the impact of vegetation, not the shape of local terrain. The velocity of water flow as determined by the down river water surface slope and loss of energy due to the flow resistance are generated by a function of the vegetation mosaic.

Determination of roughness coefficients and estimation of error range

Direct measurement of the water velocity distribution lengthwise research site and a down river water surface slope allows to determine the real value of roughness coefficients.

Water velocity and the water surface slope have been measured at the same time. It was assumed that all measured velocity profiles have the same river water surface slope. This assumption allows the use of a well-known formula by Manning (1) or Darcy-Weisbach (2) for the calculation of roughness coefficients:

$$V = \frac{1}{n}\sqrt{S_f}\,h^{2/3} \tag{1}$$

$$V = \sqrt{\frac{8ghS_f}{f}} \tag{2}$$

where: V – water velocity [m/s], S_f – down river water surface slope [–], h – water depth [m], n – Manning friction coefficient [sm$^{-1/3}$], f – Darcy-Weisbach friction coefficient [–].

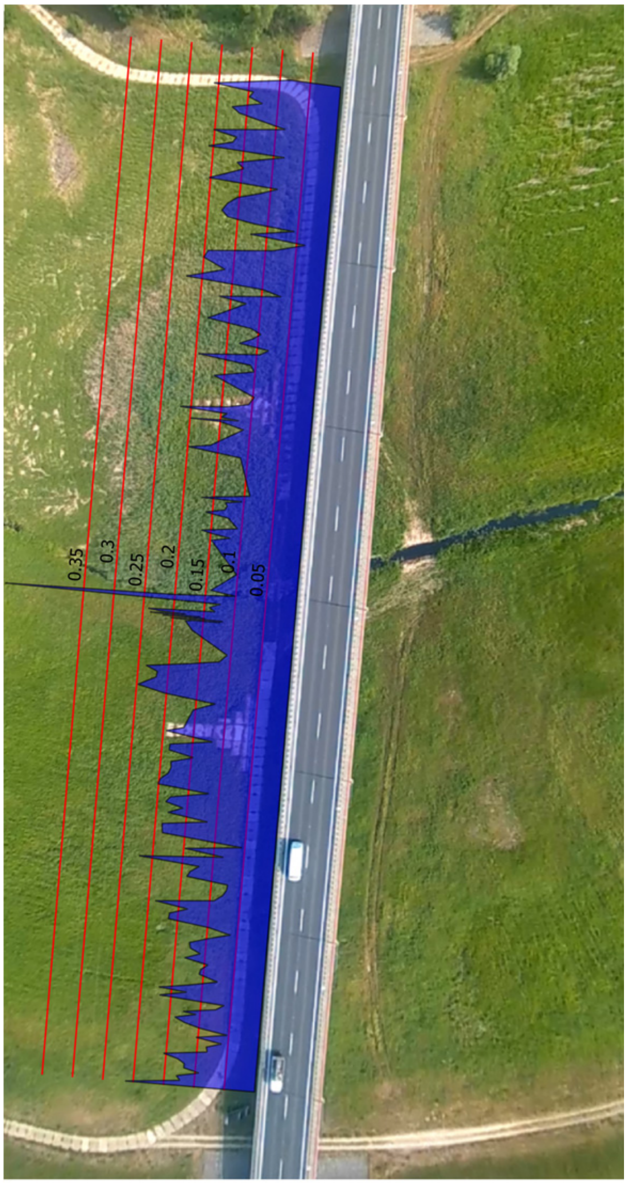

Fig. 6. Distribution of vertical averaged velocities.

On the basis of the friction coefficient value from the formula (2) the absolute roughness values in the form of substitute sand roughness k_s can be determined by using simplified by Rickert (1986) formula of Colebrook-White:

$$f = \left[-2.0\log\left(\frac{k_s}{14.84h}\right)\right]^{-2} \tag{3}$$

The results based on the formula of Manning, which assumes a constant with the depth value of friction coefficient were chosen in further analyzes.

As mentioned above ADCP StreamPro were used to measure water velocity and water depth. To measure water surface slope a high-accuracy GPS surveying equipment was used.

The calculated values of roughness coefficients for flow rate equal to 14.0 m^3/s shows Fig. 7. High variability of roughness coefficients values lengthwise research site can be seen. Table 2 shows basic statistical values for two different flows. All the basic statistical characteristics are similar. This is due to the fact that the flow energy in the both cases were similar (the average speed for both flows rates is equal to 0.09 m/s).

Table 2. Basic statistical values of Manning friction coefficient.

Flow rate [m^3/s]	Average value [s m$^{-1/3}$]	Standard deviation [s m$^{-1/3}$]	Maximum value [s m$^{-1/3}$]	Minimum value [s m$^{-1/3}$]
9.2	0.0831	0.0579	0.357	0.0212
14.0	0.0792	0.0532	0.311	0.0201

Calculated values of roughness coefficients are burdened with errors resulting from the accuracy of measuring instruments and simplifying the formula used to determine them (Huthoff and Augustijn, 2004).

The maximum measurement uncertainty Δy for complex-valued quantities was calculated according to well-known formula:

$$\Delta y = \sum_{k=1}^{N} \left| \frac{\partial y}{\partial x_k} \right| \Delta x_k = \left| \frac{\partial y}{\partial x_1} \right| \Delta x_1 + \ldots + \left| \frac{\partial y}{\partial x_N} \right| \Delta x_N \quad (4)$$

where: $\frac{\partial y}{\partial x_k}$ – partial derivative, Δx_k – maximum uncertainty of variable x_k, N – number of independent variables.

Formula (4) was applied to estimate error range of Manning friction coefficient calculated from equation (1). This equation has been turned into:

$$n = \frac{1}{V} \sqrt{S_f}\, h^{2/3} \quad (5)$$

Water surface slope was calculated according to formula:

$$S_f = \frac{H_2 - H_1}{L} \quad (6)$$

where: H_1, H_2 – elevations of water table [m], L – distance between the measuring points [m]. Maximum uncertainty of particular variables is presented in Table 3.

Table 3. Maximum accuracy of measurements.

Δv [m/s]	Δh [m]	$\Delta H_1, \Delta H_2$ [m]	ΔL [m]
5% measured value	0.02	0.01	0.05

The estimated value of the maximum error was approx. 19% of the calculated value of Manning roughness coefficients. The biggest impact to inaccuracies was associated with measuring the water surface slope, which was approx. 16%. The measurement of water table elevation in field conditions was difficult first of all because of the ripple water, which made it impossible to achieve accurate results. The maximum uncertainty of calculated roughness coefficients are shown in Fig. 7.

Such large value of the error may impair further analysis related to the impact particular plant species on flow resistance. Therefore, the authors decided to use of direct measurements of water velocity in further analyzes, which reflect the energy loss due to vegetation but are burdened with smaller error.

The botanical survey

The botanical survey revealed development of eight types of vegetation. Furthermore, a part of the surveyed buffer was completely unvegetated.

The rush vegetation dominated the survey area. Six types of typical rush vegetation have been distinguished. These were:

- *Phalaris arundinacea-Poa trivialis* (Phal-Poa)
- *Carex gracilis- Phalaris arundinacea* (Carex-Phal)

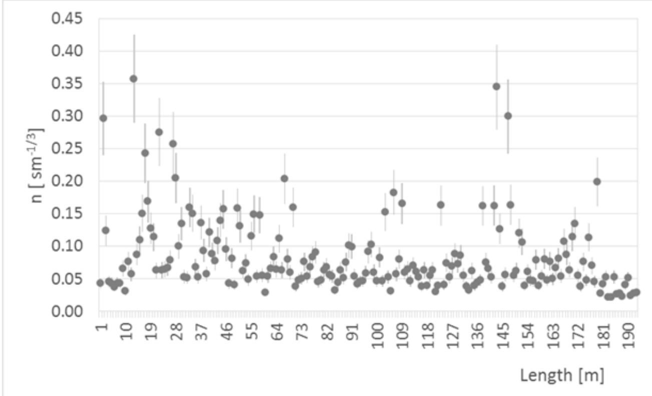

Fig. 7. Values of Manning friction coefficient along the length of study site and range error of estimation (flow rate equal to 14.0 m^3/s).

- *Phalaris arundinacea-Glyceria maxima* (Phal-Glyceria)
- *Phragmites australis-Phalaris arundinacea* (Phragmites-Phal)
- *Phragmites australis* (Phragmites)

The identified rush patches were dominated by tall-growing grasses (*Phalaris arundinacea*, *Glyceria maxima* and *Phragmites australis*), as well as sedges (*Carex gracilis*). Their share in the sward exceeded 90%. A small area was covered by *Alopecurus pratensis, Poa trivialis Poa palustris, Symphytum officinale, Lysimachia vulgaris,*

Apart from rush communities, also two types of grasslands communities have been identified. These were:

- *Poa pratense-Trifolium repens* (Poa-Trifolium)
- *Agropyron repepns-Carex gracilis-Poa trivialis* (Agropyron)

These both communities were overgrown mainly by shorter grasses and herb species. These were: *Poa trivialis, Poa pratensis, Agropyron repens, Trifolium repens, Plantago major, Polygonum aviculare, Potentilla repens*. The sword of these communities had a certain share of rushes and sedges (*Phalaris arundinacea* and *Carex gracilis*).

Relation between vegetation and flow velocity

The relationship between the floodplain vegetation and water velocity was analysed (Tables 4 and 5). The analysis of variance has been proved that the water flow velocity varies greatly against the specific types of vegetation. This dependence refers both to vegetation growing upstream and downstream of the hydraulic survey profile (Table 6).

The post-hoc analyses, of the water velocity differentiation between the downstream vegetation types showed the lowest values of *Phalaris arundinacea-Poa trivialis* and *Phragmites australis* communities (Fig. 8). In case of *Carex gracilis-Phalaris arundinacea* and *Phalaris arundinacea-Glyceria maxima*, the flow velocity was significantly higher.

Table 4. Variation of vertical averaged velocity according to types of vegetation growing in the buffer of 20 metres downstream of the measurement profile (N = 132).

Types of vegetation	V [m/s] Average	V [m/s] Important	V [m/s] Stand. dev.
Phalaris arundinacea-Poa trivialis	0.117	58	0.0416
Carex gracilis-Phalaris arundinacea	0.171	17	0.0288
Phalaris arundinacea-Glyceria maxima	0.173	19	0.041
Phragmites australis	0.134	38	0.035
Total	0.137	132	0.044

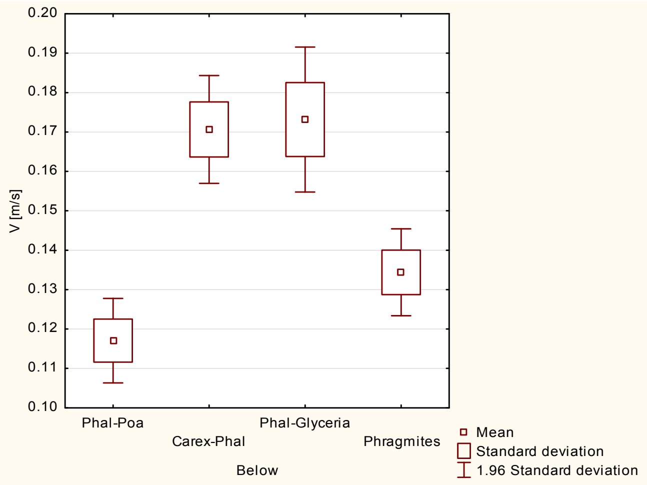

Fig. 8. Differences of water flow velocities between vegetation types growing downstream of the measurement profile.

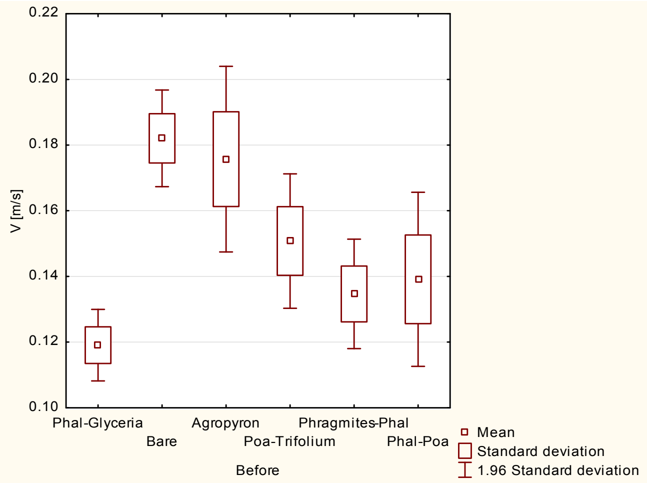

Fig. 9. The differentiation of water flow velocities against vegetation growing upstream of the measurement profile.

Table 5. Variation of vertical averaged velocity according to types of vegetation growing in a buffer of 20 metres upstream of the measurement profile (N = 168).

Types of vegetation	*V* [m/s] Average	*V* [m/s] Important	*V* [m/s] Stand. dev.
Bare	0.182	22	0.035
Phalaris arundinacea-Poa trivialis	0.139	9	0.041
Phalaris arundinacea-Glyceria maxima	0.119	51	0.040
Phragmites australis-Phalaris arundinacea	0.135	31	0.047
Poa pratense-Trifolium repens	0.151	13	0.038
Agropyron repepns-Carex gracilis-Poa trivialis	0.176	26	0.074
Total	0.145	152	0.053

The post-hoc analyses showed that the water velocity depends on the vegetation type growing in the upstream buffer of the measurement profile. The highest average velocity of flowing water was when the upstream zone was unvegetated (Bare). The very high velocity was also in case of grassland communities (Agropyron, Poa-Trifolium) (Fig. 9). The velocity was particularly low in case of the Phal-Glyceria, as well as Phragmites-Phal, as well as the Phal-Poa.

DISCUSSION

Due to the flow conditions (high dense vegetation, small compared to the width of the by-pass channel average depth, i.e. h/B = 0.006) it can be assumed that the velocity distribution depends mainly on the vegetation. Local differences in flow conditions (e.g. a large variation in the height and density of vegetation) affects the water velocity distributions in the cross section and hence also the roughness coefficient distributions. Tyminski (2012) and Kubrak et al. (2008) have observed similar effects in laboratory conditions and Knight (2013) under natural conditions. Ding and Wang (2005) analyzed the high variability of roughness coefficients obtained on the basis of the model calibration and the results of field research.

Strong correlation between the type of vegetation in the by-pass channel and the flow speed was noticed. The revealed relationship was detected in a relatively narrow profile - 20 metres upstream and 20 metres downstream of the hydrometric measurement profile. Furthermore, the impact of both upstream and downstream vegetation was confirmed. The impact of vegetation structure on water flow has been confirmed in numerous studies (e.g. Petryk and Bosmajian, 1975), but in our study it has been proved that even the such a narrow buffer (20 m) can determine flow conditions significantly.

It has been shown that rush plant communities consisting of tall-growing grasses (*Phalaris arundinacea, Glyceria maxima and Phragmites australis*), as well as sedges (*Carex gracilis*), slows the high water velocity. Hydraulic resistance is significantly influenced by the species present in the vegetation and stem diameter, density, arrangement and rigidity are key parameters influencing the flow (Naden et al., 2006). The analysed rush vegetation patches were well developed communities forming tight patches of thick stems reeds and sedges. On the other hand, grassland vegetation dominated by low species (*Poa trivialis, Poa pratensis, Agropyron repens, Trifolium repens, Plantago major, Polygonum aviculare, Potentilla repens*), influence the water flow in a more limited extent. The unvegetated zones determine a significant growth of water velocity comparing with the vegetated zones and it confirms that vegetation removal prevents the increase in hydraulic resistance (Bal et al., 2011).

Presented researches proved again that the vegetation determines flow conditions. The differences were significant even the surveyed part of the valley was covered with relatively uniform flora. It should also be noted that tree and bush vegetation was not present. The scrub and tree vegetation can influence much stronger than the grasses and herbs (Petryk and Bosmajian, 1975). Furthermore, in case of the examined grasslands, a certain share of rushes was detected and still the roughness was significantly lower than of the typical rushes and sedges. Having also considered the narrowness of the buffer

Table 6. Velocity differentiation between types of vegetation growing in a 20 meter of the measurement profile - analysis of variance.

Variable	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	p
Downstream	0.067	3	0.022	0.186	128	0.0015	15.43269	0.000000
Above	0.093	5	0.019	0.337	146	0.0023	8.051479	0.000001

(20 metres upstream and 20 metres downstream) the type of vegetation appeared as extremely influential factor to the flow conditions.

CONCLUSIONS

In situ measurements of velocity distribution in real flood conditions confirmed that the vegetation has a significant impact on the water flow conditions. A large variability of both vertical and horizontal velocity distribution is evident. This causes difficulties in the flow modelling process on overgrown areas regardless of the adopted mathematical model of the phenomenon.

The velocity of flowing water depends greatly on the type of vegetation growing both upstream and downstream. Rush vegetation consisting of tall-growing grasses (*Phalaris arundinacea, Glyceria maxima* and *Phragmites australis*), as well as sedges (*Carex gracilis*) strongly decrease the flow velocity. On the other hand, grassland vegetation with medium low-growing species (*Poa trivialis, Poa pratensis, Agropyron repens, Trifolium repens, Plantago major, Polygonum aviculare, Potentilla repens*) have a much more limited impact on water flow.

The results of the work focused on estimating the impact of vegetation on velocity distributions which resulted from a relatively large error of determination of the roughness coefficients. Further activities will be directed to the preparation of the research site (primarily installation of high precision devices for measuring the water table elevation) in order to enable a more accurate determination of the roughness coefficients and assign the values to particular species of vegetation.

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